Performance Measurement and Analysis of Multi-layer Insulation Material (MLI) From 20 K-300 K

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Abstract. This paper introduces a cryogen-free high vacuum multi-layer insulation material (MLI) measurement system based on a G-M cryocooler, which uses the steady-state axial heat flux method for heat measurement. The system enables cold boundary temperatures from 20 K to 120 K, and the thermal insulation performance of a commonly used MLI produced by double aluminized-Mylar and fiberglass paper is tested by this system. A modified numerical analysis method for the heat transfer coefficients of the MLI is introduced, which sets temperature as a variable. The heat transfer of the MLI is analysed according to the test and the calculation result, and thereby some MLI performance optimization method is proposed.

1. Introduction

nomenclature	
q	heat flux (W/m^2)
V	volume flow rate (m^3/s)
T	temperature (K)
P	pressure (Pa)
R	radius (m)
l	length (m)
k	heat transfer coefficient ($W/(m \cdot K)$)
Q	heat (W)
A	area (m^2)
r	heat resistance ($(m \cdot K)/W$)
M	gas molecular mass (g/mol)
f	relative mass of the spacers
C	empirical constant
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant

ε	emissivity
Subscript:	
s	solid conduction
q	residual gas conduction
r	radiation
N	Serial number of the layer

Cryogenic technology is widely used in aerospace, magnetic resonance imaging (MRI), infrared detection, quantum computing, cold chain, liquid hydrogen vehicles and other aspects[1, 2]. The maintenance of cryogenic is a key element in its application, while cryogenic maintenance demands a continuous supply of cooling capacity and thermal insulation. High vacuum multi-layer insulation (MLI) uses vacuum to reduce gas convection, high reflective material to reduce radiation. Thus, it is recognized as one of the best thermal insulation methods and is used in broad cryogenic systems[3].

It is necessary to measure the performance before studying the heat transfer mechanism of MLI, thus there were some MLI measurement apparatuses built by researchers[3]. A large-scale industrial measurement platform built by NASA from liquid hydrogen temperature to liquid nitrogen temperature or normal temperature is shown in reference[4]. While according to reference[5], MLI has different performance at different temperatures. This is the reason that affects the reflector's emissivity and the structural materials' thermal conductivity, affecting the radiation heat transfer, heat conduction and the residual gas conduction of MLI.

For application in a wider range of temperatures at low temperatures, it is necessary to develop a new MLI performance measurement apparatus which can be used in different temperature ranges. In addition, the effect of temperature on each component must be considered and the main heat transfer methods should be identified to perform numerical calculations of MLI performance. Finally, MLI performance improvement methods for different temperature regions will be proposed based on the measurement and analysis results.

2. MLI performance measurement

2.1 Measurement system

This system uses the steady-state axial heat flow method, as shown in Figure 1. In this system, the cooling power of the cryocooler is transferred to the cold boundary through a metal rod that has been calibrated before use and is therefore called a calibration rod. The heat flux can be determined based on the temperature gradient on the rod through Eq.2-1. When the system reaches thermal equilibrium, the temperature difference between the two ends of the rod at a specific cold boundary temperature corresponds to a certain heat flow and the heat flow through the rod is equal to the heat flow through the tested MLI. After the measurement system reaches thermal equilibrium, a uniform temperature gradient formed on the rod. The design of the device was described in detail in our previous article[6].

$$q = k \cdot \Delta T \tag{2-1}$$

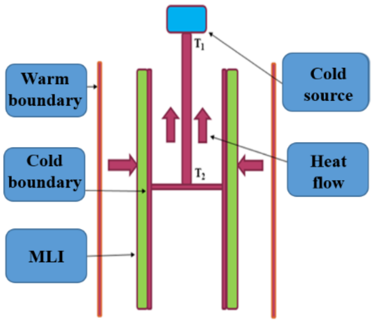

Figure 1. The heat flow chart of the measurement system

2.2 T*est specimen*

The material tested in this paper is made of double aluminized-Mylar and fiberglass paper. Every ten layers are made into a group by laser cutting technology, and three groups are superimposed in this experiment. The thickness of one piece of Mylar is 0.12 mm and the aluminizing at each side is 600 Å. The thickness of one piece of glassfiber paper is 0.4 mm, and the total thickness of the test specimen is 10.5 mm, and the layer density is about 28.5 layer/cm. The photograph of the tested material is shown in Fig.3. Before the specimen is tested, it would be dried in a vacuum oven for 12 hours at a temperature of 100 ℃.

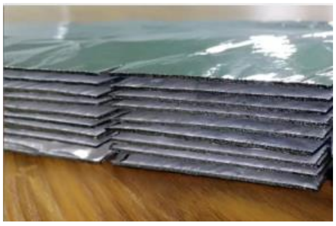

Figure 2. photograph of the tested specimen

3. Experimental results

A Keithley 340 temperature controller is used to control the temperature of the top of the calibrated rod which is the cold boundary, and the vacuum chamber is used as the warm boundary. The warm boundary temperature is maintained at 25 ℃ by air-conditioning. Fig.3 shows the variation of the heat flux through the MLI with the cold boundary temperature.

According to Fig.3, with the increase of the cold boundary temperature, the heat flux of the measured MLI decreases, and the graduation of the curve becomes steeper, which means the increment of heat flux decreases with the decrease of cold boundary temperature. The heat flux through the MLI under test increased by 39.0% when the cold boundary temperature decreased from 120 K to 20 K. When the cold boundary temperature decreased from 77 K to 20 K, the heat flux increased by 17.7%.

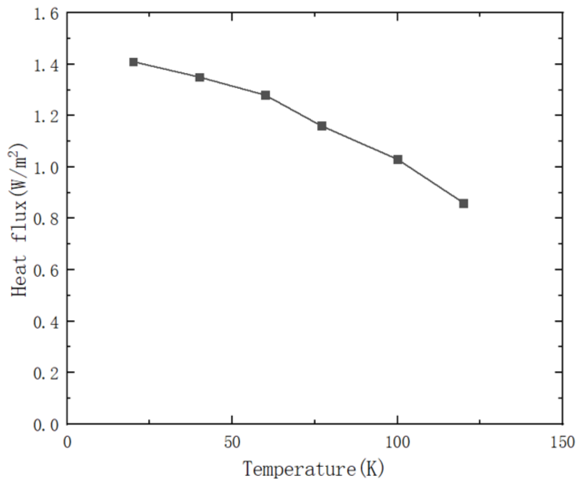

Figure 3. Curve of heat flux with cold boundary temperature

4. Heat transfer analysis and calculations

In this section, the heat transfer coefficients between two adjacent reflectors at different temperatures are analysed. To facilitate heat transfer analysis, the heat flux is divided into three independent ways, and the heat flux between the two adjacent reflectors can be represented as Eq.4-1,

$$q_{total} = q_s + q_g + q_r \tag{4-1}$$

According to the Layer-by-Layer model, the solid conduction heat transfer q_s can be calculated by the following equation[5].

$$q_s = k_s(T_{N+1} - T_N) \tag{4-2}$$

$$k_s = C_1 \cdot f \cdot (-0.034 + 0.0035 \cdot T - 1.315 \cdot 10^{-5} \cdot T^2 + 1.733 \cdot 10^{-8} \cdot T^3)/DX \tag{4-3}$$

Where, C1 is the empirical constant, DX is the thickness of a piece of spacer, m.

Eq.4-4 is utilized to calculate residual gas conduction under a vacuum environment. In terms of residual gas heat transfer, the point is to calculate the total coefficient of the relationship between pressure and temperature, and the pressure in the vacuum chamber can be obtained through the previous test results at around 10^{-4} Pa. Considering that the pressure between the layers is 1-2 orders of magnitude higher than the vacuum chamber, thus the heat conduction coefficient of the residual gas can be Eq.4-5

$$q_g = a\left(\frac{\gamma + 1}{\gamma - 1}\right)\sqrt{\frac{R}{8\pi}}(T_{N+1} - T_N)\frac{p}{\sqrt{MT}} \tag{4-4}$$

$$k_g = 1.12 \times 10^{-5} k \cdot a \cdot (T_{N+1} + T_N) \tag{4-5}$$

where k and a are thermal adaptation coefficients related to the gas and temperature.

Radiation heat transfer can be calculated by Stefan-Boltzmann law. According to reference[7], the emissivity of the reflector changes with the temperature. The radiation heat transfer coefficient of the adjacent reflectors of double aluminized-Mylar MLI is Eq.4-6,

$$k_r = \frac{\sigma \cdot (0.0131 + 4.643 \times 10^{-5} T_N)(T_{N+1} + T_N) \cdot (T_{N+1}^2 + T_N^2)}{1.9869 - 4.643 \times 10^{-5} T_N} \tag{4-6}$$

5. Calculation results and discussion

It can be concluded from the modified equations that the total heat transfer coefficient k_N between the N+1 and N layer is,

$$k_N = k_s + k_g + k_r \tag{5-1}$$

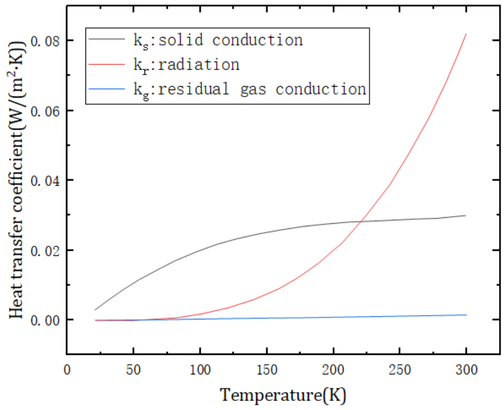

Fig.4 Three kinds of heat transfer coefficients between the adjacent layers

As Fig.4 shows, the comparison of the three kinds of heat transfer ways between two adjacent reflectors at different temperatures, and the calculation range is from 20 K-300 K. In the high vacuum environment, the residual gas thermal conductivity proportion is too small to ignore. The solid heat transfer coefficient is the largest in the low temperature position. When the temperature is above about 200 K, the increasing trend of thermal conductivity of spacer material with temperature slows down and the radiation heat transfer coefficient increases sharply, reaching almost two orders of magnitude larger than the solid heat conduction at ambient temperature.

$$E = k_s / k_r \tag{5-2}$$

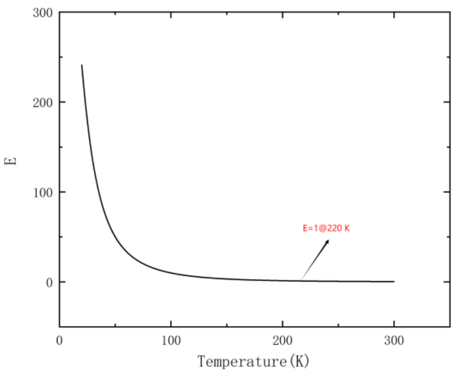

Fig.5 The curve of the ratio of solid heat conduction and radiation between the adjacent layers

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Parameter E shown in Eq.4-6 and Fig.5 is introduced to characterize the proportions of the two main heat transfer ways. The calculation result along with Fig.5 can be used to point out directions for the MLI performance improvement. Specifically, in the design optimization of the MLI structure, the performance can be improved by increasing the thermal resistance of the spacer in the low temperature region, such as increasing the thickness of the spacers and reducing the contact area between the spacers and the reflectors, etc. While in the high temperature position, the proportion of radiation heat transfer is the largest, so the thermal resistance of radiation should be increased, such as increasing the number or density of the reflectors or using materials with higher emissivity as the reflector.

6. Conclusion

A liquid cryogen-free measurement system with a G-M cryocooler as the cold source was used to test the performance of a commonly used MLI, with cold boundary temperature from 20 K to 120 K and warm boundary temperature at ambient temperature. The performance of the tested MLI at different boundary temperatures showed that when the cold boundary temperature decreased from 120 K to 20 K, the heat flux through the tested MLI increased by 39.0%. When the cold boundary temperature dropped from 77 K to 20 K, the heat flux increased by 17.7%. In addition, we put forward a modified MLI calculation model with temperature as a variable. The comparison of three kinds of heat transfer ways in adjacent reflectors in the range of 20 K-300 K was calculated and discussed, and the MLI performance improvement methods were proposed based on the calculation results.

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